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Bi-directional 120 km Long-Reach PON Link Based on Distributed Raman Amplification

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Abstract— **We propose and demonstrate a bidirectional PON link with 120 km reach and symmetric up and down stream data rate of 10 Gbit/s. Lossless transmission was achieved with >40 dB of received OSNR.**

I. Introduction

Long reach access networks have been proposed as a promising way to reduce the unit cost of bandwidth in fiber-to-the-premises (FTTP) solutions [1], [2]. Long-reach access is based on the idea of using a high-capacity, high-split passive optical network (PON), with a reach of $\sim$ 100 km, to combine optical access and metro into a single system [3]. Systems with symmetric upstream (US) and downstream (DS) data rates of 10 Gbit/s, split factors of 1024 and link lengths up to 135 km have been reported [1], [3]. These demonstrations, however, make use of advanced schemes such as FEC and EDC [1] and separate fibers and amplifiers for the US and DS signals [1], [3]. We recently proposed a simple, bi-directional, 80 km PON link based on distributed Raman amplification (DRA) and non-zero dispersion-shifted fiber (NZDSF) [4]. This link design is advantageous since it combines the US and DS signals on a single fiber and features superior noise performance compared to terminal-based amplification, due to the distributed Raman gain. Furthermore, the low dispersion parameter of the NZDSF reduces the need for dispersion compensation.

In this paper, we demonstrate error-free, bidirectional transmission of 10 Gbit/s/channel across a 120 km PON link, with no observed penalty due to bi-directionality, with positive net gain for all channels and a received OSNR after transmission in excess of 40 dB. The high on-off gain and good noise performance is obtained using a combined forward and backward pumping scheme and could potentially enable high splitting factors. No dispersion compensation was used.

II. Experimental setup and results

The proposed bidirectional long-reach PON link, along with the surrounding networks, is shown in Fig. 1. The PON link is connected to the metro core node and has a typical length of $\sim$ 100 km. The link delivers signals to and from the local exchange, where the dense wavelength division multiplexing (DWDM) channels are further distributed to the splitting points at the access part of the network.

The experimental setup is shown in Fig. 2. Two Mach-Zehnder $LiNbO_3$ modulators (MOD) are used to generate the US and DS signals. The electrical signals (a $2^{31}-1$ PRBS pattern) are obtained from the data and inverted data outputs of a pulse pattern generator (PPG). The optical wavelength of the upstream channel is 1548.0 nm and 1550.4 nm for the downstream channel. The PON link is composed of 120 km TrueWave®RS with a total passive loss of 24.6 dB and a total dispersion of 550 ps/nm at 1550 nm. The employed optical receiver uses no optical pre-amplification.

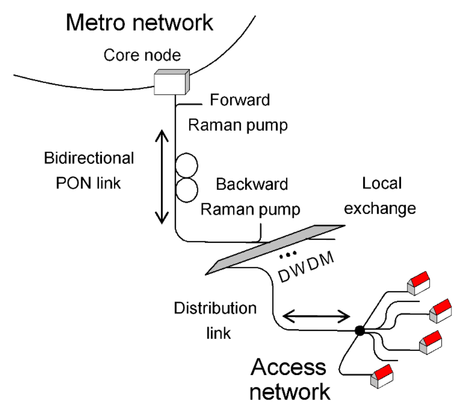

Fig. 1. Extended reach access system based on a single fiber, bidirectional PON link with distributed Raman amplification.

The upstream and downstream signals are coupled into the PON link using two optical circulators placed at each end of the link. Before transmission, the signals are multiplexed with two co-propagating Raman pumps using a coarse WDM. In this architecture, the signals will see both co- and counter-propagating pumps during transmission. The US and DS signal power into the link (after the WDM) is -1.3 dBm and -2.3 dBm, respectively. The wavelengths of the upstream pumps are 1437 nm and 1465 nm and the optical input powers are 165 mW and 180 mW. The wavelengths of the downstream pumps are 1427 nm and 1456 nm with respective input powers of 231 mW and 279 mW. At the end of the link, the circulator routes the signal to the receiver, where an optical bandpass filter (BPF) is used to reject the amplified spontaneous emission (ASE) and backscattered power from the counter-propagating channel.

In the bi-directional case, both the US and DS channels are

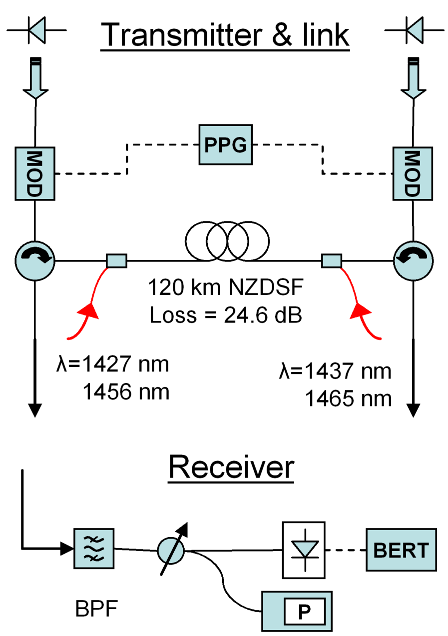

Fig. 2. Experimental setup used to measure the bit-error rate performance of the link.

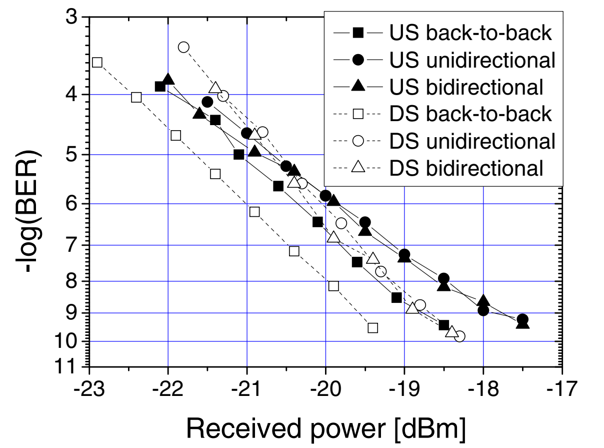

Fig. 3. Bit-error rate as a function of received power for the up- (solid) and downstream (dashed) channels.

on and the net gain is measured to 2.9 dB and 2.2 dB, for those channels, respectively. The corresponding on-off gain is 27.5 dB and 26.8 dB, which gives rise to a signal power at the output of the link of 1.6 dBm (US) and -0.1 dBm (DS). The received OSNR (noise spectral density measured in a 0.1 nm resolution bandwidth) is measured before the BPF and is found to be 40.9 dB and 41.9 dB for the US and DS, respectively. With only a single channel turned on (uni-directional case), the gain and OSNR of both channels increased by 0.2 dB, indicating a very low level of gain saturation.

Simulations based on a numerical rate equation model, which includes contributions from ASE noise, backscattering and fiber data of the experimental fiber, was found to agree well with the experimental gain values, with on-off gain values within 1 dB of the experimental values. We also calculated the level of multi-path-inference (MPI) noise due to double-Rayleigh backscattering (DRB). This effect is known to be a common limitation of high-gain Raman amplifiers. We found the MPI contribution of the system to be less than -40 dB for both the US and DS channel, meaning that MPI is not limiting the performance and can be neglected at these pump powers.

Measurements of bit-error-rate (BER) as a function of input power are shown in Fig. 3 for both channels. The channels have been characterized in the case of back-to-back (no transmission), after uni-directional transmission and after bi-directional transmission. The sensitivity is defined as the minimum power at which a BER of 10^{-9} can be obtained. We find the back-to-back sensitivities to be -18.8 dBm and -19.6 dBm, for the US and DS channel, respectively. After unidirectional transmission, we find a sensitivity penalty of 0.8 dB (US) and 0.9 dB (DS) and for the bidirectional case, the penalty is 0.7 dB (US) and 0.8 dB (DS), compared to back-to-back. All in all, penalties of less than 1 dB are found in all four cases and no performance degradation was found when comparing bi- to uni-directional transmission.

To illustrate the link potential, a power budget for a PON system with 1/8 splitting ratio can be estimated. By assuming a loss of 6 dB in the local exchange DWDM, a split loss of 9 dB, a combined connector and splice loss of 1.5 dB and up to 4 dB of loss due to transmission ($10 - 20$ km) in the access network, the total loss add up to 20.5 dB. With the current output power of $\sim$1 dBm and receiver sensitivity of -18 dBm, a modest increase in gain of 3-6 dB would provide an acceptable power redundancy for practical use. The gain increase could be obtained by a simple increase in the pump powers or signal input power. The power budget shows a clear potential for the DRA-based long-reach PON link, especially for systems with low splitting factors and high capacity.

III. Conclusion

We have tested a simple design for a long-reach PON link, based on a single bi-directional NZDSF fiber employing distributed Raman amplification. After 120 km of transmission, without any use of dispersion compensation, we find received OSNR values in excess of 40 dB, transmission penalties limited to $\sim$ 0.8 dB and no increased penalty due to the bi-directional operation. To conclude, we find the bidirectional long-reach PON link to be an excellent candidate for future long-reach access systems.

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